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AN ATTEMPT TO DETECT THE IMPORTANCE OF TURBULENT BOUNDARY LAYER--ETC(U)
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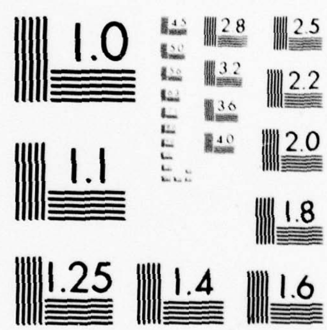

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Report EW-4-79

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An Attempt to Detect the Importance of Turbulent Boundary Layer in Ship Wave Resistance,

10 S. M. Calisal

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*Assistant Professor
Naval Systems Engineering Department
U. S. Naval Academy
Annapolis, Maryland

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AN ATTEMPT TO DETECT THE IMPORTANCE OF TURBULENT BOUNDARY LAYER IN SHIP WAVE RESISTANCE

S. M. CALISAL

EW-4-79

ABSTRACT

The Reynolds number of a ship model is increased artificially by using a flat plate leading the model. The turbulence level of the flat plate boundary layer is also altered. A decrease in the calculated wave resistance and measured residual resistance is observed within the Froude number range $2\cdot<Fr<\cdot 4$. The results indicate a viscous wave interraction which can be formulated in terms of the visco elastic properties of turbulent flow. A possible formulation using this procedure is also indicated.

ACKNOWLEDGEMENT

The author would like to thank the U.S. Naval Academy Research Council for its grant in support of this study. The continuous help recieved by Ronald Altmann, John Hoyt and Paco Rodriguez during the experimental phase must also be acknowledged with sincere appreciation.

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INTRODUCTION

Ship wave resistance is formulated in terms of kinematic quantities as given by Wehausen (1960). The resulting equation is a Laplace equation which reflects the continuity equation and irrotational flow condition. The boundary conditions related to this formulation are the impermeable boundary condition at the ship hull ($v.n = Vn$), the free-surface condition at the free surface and the radiation condition. This last condition ensures that the ship's waves exist only astern of the ship. In a more general physical problem involving a process, one normally needs additional equations such as energy balance, constitutive equations, etc. Such equations are avoided in the above-mentioned formulation. The problem, mathematically well-posed in terms of kinematic quantities, can then be solved with the help of potential theory or by numerical methods (Bai, 1977). Perturbation methods used for the solution of potential flow linearize the problem and solutions corresponding to different orders of perturbation can be obtained.

From the point of view of dimensional analysis, ship resistance can be studied in terms of three non-dimensional numbers. The resistance coefficient Cr can be represented in terms of Reynolds (Re) and Froude (Fr) numbers. Symbolically:

$$Cr = f\ (Re, Fr)$$

A very practical but also very questionable hypothesis by Froude gives the functional relationship for f as:

$$f\ (Re, Fr) = f_1\ (Re) \dot{+} f_2\ (Fr)$$

This relationship is still the basis for estimating ship resistance based on model test data. Function f_1 is the frictional resistance coefficient calculated using a universally accepted formula, and f_2 is

the experimentally obtained residual resistance coefficient. The simplicity of the procedure is very attractive from an engineering point of view, but it does not include a term for possible interactive effects. It is perhaps for this reason that additional resistance correction terms must be defined for ships with non-standard, basic geometry. The term f_2, "residual resistance", or a term related to it, "wave resistance" can also be calculated from information obtained by wave survey methods (Eggers, Sharma, Ward, 1967). A comparison of calculated wave resistance and experimentally obtained residual resistance usually shows a discrepancy between the two with residual resistance being larger.

Theoretical wave resistance calculation such as Michell resistance usually estimates a higher wave resistance value than experimentally obtained values given by wave survey analysis. Even though new theoretical developments (Baba 1977) provide a better correlation between theoretical and experimental results, additional problems remain in the formulation of the ship wave resistance problem. They are:

1. Turbulent flow surrounding the hull generates a "process", which extracts energy from the main flow and has special characteristics. This is not represented in the present formulation.

2. The impermeable boundary condition at the hull surface $v \cdot n = Vn$ becomes meaningless for a no-slip boundary condition such as $v = 0$ at the hull surface.

Certain reformulations therefore suggest themselves. Historically, the second problem has been solved by readjusting ship half-breadth values

by an amount proportional to the displacement thickness of an equivalent flat plate flow (Landweber 1978). The first question has not been studied to the author's knowledge. To detect a possible interaction or dependence between boundary layer flow and wave generation, some experimental studies were done at the U. S. Naval Academy. The purpose of the investigation was to alter the boundary layer parameters of the hull, to measure the wave spectra and to calculate the wave resistance by means of a wave survey method.

EXPERIMENTS

Experiments were performed in the 120 ft Naval Academy towing tank. A series of experiments was planned to change the boundary layer flow characteristics of the model. This was accomplished by towing a flat plate aligned with the centerline of the model. The flat plate was equipped with turbulence generating studs, as was the model. The model and the flat plate were free to trim and surge. The model used was the well-studied series 60, block 60 model. The characteristics of the model are given in table 1. The flat plate was a smooth aluminum plate normally used for the measurement of flat plate resistance. The same flat plate in the next series of experiments was covered by 3M40 grid sanding cloth to generate a higher turbulence level. This set of experiments is labelled "rough plate" experiments. The total resistance of the model was also measured by an electronic dynamometer. Two sonic wave-height gages, one 17 inches, the other 24 inches from the center line, were poisitioned to record the longitudinal wave height values. At five selected speeds and within the Froude number interval $.2 < Fr < .4$ longitudinal wave height records of the hull, the flat plate, and the flat plate plus the hull were obtained. Each run was repeated twice

to check the repeatability of the procedure. The speed of the model and two wave height electronic signals were recorded on magnetic tapes of a Tektronix 4051 minicomputer. Multiplexing and analog to digital conversion were done by the DAS-2, a locally manufactured data acquisition system. Calibration of the resistance-dynamometer and the wave height gages were done before and after the tests. An electronic signal was also recorded on the tape to indicate the physical location of the model with respect to the wave height probes.

ANALYSIS OF DATA

Calibrated wave-height data were stored in files in the main computer. Data that correspond to the "model only" configuration were used to obtain the wave resistance values of the series 60 model. The resulting resistance coefficients were then compared to those published by Ward (1964), and a good agreement between them was observed. The computer program used for this calculation is a well-tested program specifically coded for wave resistance computation through wave survey methods (Reed, Sharma 1969). A certain amount of discrepancy was observed between wave spectra and wave-resistance values corresponding to different wave probes. This is to be expected, and it results mainly from the lateral location of the probes (Ward 1976).

In the analysis of the data corresponding to the model plus flat plate cases it is assumed that the interaction term in the wave profile will be negligible. If η represents the total wave height and ϵ_h and ϵ_p are the perturbation parameters corresponding to the hull and plate velocity potentials, to the first order in, ϵ η can be written as:

$$\eta = \varepsilon_h \eta_h + \varepsilon_p \eta_p + \varepsilon_h \varepsilon_p \eta_{hp} + 0(\varepsilon^2)$$

where ε_h is the wave pattern generated by the hull alone, η_p the wave generated by the plate and η_{hp} the interaction term. In thin ship theory the values of ε_p is usually assumed to be proportional to ε_h the beam to length ratio. ε_p is therefore very small compared to ε_h and, in fact, $\varepsilon_h \varepsilon_p$ will be smaller than ε_h^2, which corresponds to the second order velocity potential for the hull. Based on this argument the wave height is assumed to be of the form:

$$\eta = \varepsilon_h \eta_h + \varepsilon_p \eta_p + 0(\varepsilon^2)$$

As η and η_p are measured separately, any change in η_h is assumed to originate from the changes in the boundary layer surrounding the hull. The wave height record corresponding to the hull plus flat plate configuration can therefore be "corrected" by subtracting the wave profiles corresponding to the plate alone. "Corrected" wave profiles are then used to find the corresponding wave spectra and wave resistance of the hull with an altered boundary layer.

Identical record lengths are used for runs corresponding to the same Froude number. This is accomplished by using an interactive computer program and the curser on the screen of the terminal.

Residual resistance values are also obtained for the model following a plate. For this configuration a frictional resistance coefficient is estimated, as explained in appendix A.

The following formulas are used for the calculation of "wave resistance". The variable ko = g/c^2 is used to nondimensionalize lengths, g being gravitational acceleration and c the speed of the ship. The Fourier transform of the nondimensionalized longitudinal record is obtained as:

$$C(s, y) + i\,S(s, y) = \int_{-\infty}^{\infty} \eta(x, y) \exp(isx)\, dx.$$

The value $(C^2 + S^2)^{\frac{1}{2}}$ is usually called amplitude. The nondimensional wave resistance is then given by:

$$\overline{Rw} = \frac{1}{\pi} \int_0^\infty \frac{s^2 - 1}{s^2(2s^2-1)} (C^2 + S^2)\, du$$

where $s = \sec\Theta$, $u = \sec\Theta \tan\Theta$, and Θ is the direction of the propagation wave numbers and are kinematically connected.

Nondimensionalized wave resistance is defined as:

$$\overline{Rw} = \frac{Rw\ \ ko^2}{\rho\ c^2}$$

where Rw is the dimensional wave resistance, and ρ the density of the fluid. All other force coefficients C_i in this report are defined as:

$C_i = \frac{R}{\frac{1}{2}\rho c^2 S_w}$, where R is the force and S_w the wetted surface area.

EXPERIMENTAL RESULTS

A typical wave height record is given in Figure 1. Reflection waves from the tank walls can be observed past the data point 275. The numbers in the figure indicate the number of points defining the record. Figures 2 to 5 show amplitude spectra obtained for model and rough plate configurations. The nondimensionalized transverse wave number is represented by "S". Computed wave resistance values are also indicated in the figures. For wave resistance computation the contributing portion of the spectrum is in the range $1 \leq s < 3$. In this interval the spectra obtained from the different channels show similar behavior. Discrepencies increase as the Froude number increases. Intuitively, one can claim that channel 2, which corresponds to a longer wave record closer to the tow line, is probably more accurate, as it contains more information about the wave system.

Computer wave resistance coefficients for the hull alone are reproduced in Figure 6. Except for one point all values compare well with the curve

previously obtained by Ward (1964). The values obtained from data labelled channel 2 are consistently smaller than the wave resistance coefficients corresponding to channel 1. For this reason the results of the different channels have been compared separately.

Figure 7 shows the wave resistance values corresponding to different configurations. It can be oberved that wave resistance coefficients corresponding to a model trailing a plate are lower than the ones corresponding to the hull only configuration. The values corresponding to the model plus rough plate are in most cases the lowest. Figure 8 gives similar results as obtained from channel two. In figures 11 to 15 spectra corresponding to different configurations are given. The comparison of spectra at about s = 1, or the portion that corresponds to transverse waves, shows that the amplitude value obtained for the model alone remained larger than the values corresponding the model plus plate, and the model plus rough plate configurations. The amplitude value corresponding to the model with plate, in the same range for s, was observed in most cases to be higher than the one for the model with rough plate.

Finally, Figure 9 gives a comparison of the residual resistance values derived from measured total resistance values and frictional resistance values, as explained in Appendix A. This procedure shows that the residual resistance of the model following a flat plate is larger than the residual resistance of the model alone. But at the same time the residual resistance of the model following a rough plate is seen to be slightly lower than the residual resistance of the model following a flat plate. The first result is expected, as the laminar flow region corresponding to a smaller frictional resistance coefficient around the bow is replaced by a turbulent flow region corresponding to a larger frictional resistance

coefficient. The increase in residual resistance is in fact misleading. The second result, on the other hand, is parallel to results obtained by wave survey techniques. Figure 10 shows the frictional resistance coefficients used for these computations.

The results can be summarized as follows:

1. The boundary layer which is altered, in this case thickened, by the presence of a flat plate caused a decrease in the measured wave resistance.
2. An increased turbulence level further decreased the measured wave resistance, but to a smaller degree. A similar decrease was also observed in the residual resistance values based on measured total resistance.

Some of the changes in the computed wave resistance may be due to an interaction term ($\varepsilon_p \; \varepsilon_h \; \varepsilon_{hp}$) neglected in this study. However, the effect of an increased turbulence level is not included in these wave resistance calculations. The change measured in the wave resistance coefficient can therefore be expected to be due mainly to a change in Reynolds scaling or turbulence levels. The fact that both of these changes decrease the resistance coefficient suggests a new modeling of the ship wave resistance problem. Variations observed in the wave resistance coefficients indicate that boundary layer turbulence causes the "absorption" of a certain amount of energy from the primary flow or works as a "damper". This type of behavior can be studied by assuming that turbulence works as a "viscoelastic material" as formulated by Crow (1968), Lumley (1970). Material properties of the turbulent boundary layer can in fact be selected to reflect a change in the turbulence level. A viscoelastic medium surrounding the hull will generally decrease the normal velocity V_n of the ship motion to V_n^1, and the potential flow will therefore be subjected to V_n^1, less than V_n. Standard thin ship wave resistance theory can then be applied to the outer

potential flow based on the relationship $V_n^1 = \vec{v} \cdot \vec{n}$ as the new boundary condition where V is the velocity of the flow and n is the unit vector normal to the ship hull. The overall modeling will therefore include not only the kinematics of the flow (potential theory) but also an energy balance. This formulation has still shortcomings, as the velocity profile in the boundary layer and its related possible effects are not included in the formulation.

DISCUSSION AND CONCLUSION

The Reynolds number of the model was artificially changed for the model. This should be interpreted to be a variation in the boundary layer parameters such as boundary layer thickness, displacement thickness, friction velocity, etc. The superposition of the wave systems and neglect of the interaction term are based on the argument that the interaction term will be smaller than the second order term in the potential flow computation for the hull alone. This interaction term, on the other hand, can be calculated at least within the application of potential theory. For an ideal flat plate one expects no surface disturbance except for end effects and boundary layer effects. A well defined wave system was recorded however and was used to obtain the "corrected" wave petterns. The wave patterns "corrected" to the first order showed a consistent change in their spectra at different speeds of interest which is interpreted to be a boundary layer-wave generation interaction. This interaction term is seen to be a function of turbulence intensity and Reynolds number.

Most of the results indicated should be seen in relationship to the spectra given in Figures 11 to 15 rather than to the calculated wave resistance values alone, even though they also indicate the same trend.

The relative changes in the magnitude of computed wave resistance coefficients and in residual resistance coefficients due to an increase in the turbulence level are not equal to each other for the same Froude number, This suggests that a "form resistance" coefficient is possibly also altered by an increase in the turbulence intensity. A possible effect is the change in the separation region astern of the model.

The results of these experiments and the others reported earlier can be summarized as follows. Experiments reported in Calisal 1972 for a model with stern suction showed that the wake following a ship model does not significantly alter model wave resistance. Calisal 1978 showed that moderate boundary layer suction does not significantly change upstream boundary variables and therefore cannot relaminarize upstream flow. Downstream boundary layer variables on the other hand are affected by suction but not relaminerized. Moreno, Perez-Rojas, Landweber (1975) reported that a large scale change in the hull roughness decreases the model wave resistance, and they interpreted this to be a wake-wave resistance interaction. The present experience on the other hand tends to indicate that rather than the wake, the turbulence level immediately surrounding the hull and the boundary layer parameters, are responsible for the change in residual or wave resistance. The common denominator of the above experimental results is that the boundary layer parameters surrounding the ship play a significant role in ship-wave generation. The wake following the ship is not therefore as important as the ship boundary layer, which must be defined and used as an input for wave resistance calculations. Appendix B given a possible redefinition of the boundary condition about the hull to include inviscid flow effects.

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APPENDIX A

ESTIMATION OF FRICTIONAL RESISTANCE

A simple formulation based on the ITTC 57 curve was used to estimate the frictional resistance of the model following a flat plate. From the known total resistance coefficient of the model the frictional resistance coefficient was subtracted and the difference labelled the residual resistance coefficient.

model flat plate

Let the model and flat plate move at the same velocity. We neglect the effect of the distance which separates the model and the plate.

Since curves such as ITTC 57 represent an integration of shear stress along the length of the plate, the frictional resistance of the combined system per unit depth can be estimated as;

$$C_f^* = \frac{R_f^*}{(\frac{1}{2}\rho L V^2)^*}$$

(*) quantities refer to the combined hull plus plate configuration. The frictional resistance coefficient of the plate itself is:

$$C_f^P = \frac{R_t^p}{(\frac{1}{2}\rho \ell V^2)P}$$

The estimated frictional resistance coefficient for the following model is:

$$C_f^m = 2\, C_f^* - C_f^P$$

since the length of the model is equal to the length of the flat plate

APPENDIX B

THE BOUNDARY CONDITION ABOUT THE SHIP SURFACE FOR THE CALCULATION OF OUTER IRROTATIONAL FLOW

As viscous effects are excluded in the computation of potential flow, the boundary condition about the ship boundary should reflect four effects:

1. The flow generated by the ship geometry in the direction normal to the hull surface V_n. This will be labelled GEOMETRIC flux.

2. The flow into the boundary layer due to the boundary layer thickening. This will be labelled boundary layer INFLUX V_i.

3. The shift in the stream lines as the boundary layer slows down fluid close to the impermeable surface. This effect will be labelled STREAM LINE SHIFT.

4. Energy absorption from the main flow by the turbulent flow or VISCOELASTIC effect.

The following formulation covers these 4 components. First, the boundary condition for irrotational flow will be satisfied at an arbitrary permeable boundary close to the hull. For simplicity this boundary will be at the boundary layer thickness δ. The influx velocity V_i can at least be computed for an equivalent flat plate such as:

$$V_i = U_\infty \cdot \delta_x \; ; \; V_i = 0.296 \, U_\infty \left(\frac{U_\infty x}{\nu}\right)^{-1/5}$$

V_i is therefore more effective about the bow region where the rate of increase for δ is larger. As the boundary layer thickness increase, it will also represent the stream line shift.

The viscoelastic effect has not been used before and it will represent the decay of V_n within the turbulent boundary layer. The viscoelastic

effect can be expressed as:

$$V_n^{\ 1} = f\,(V_n\,,\ P_i)$$

where $V_n^{\ 1}$ is the geometric flux as observed at the boundary layer thickness, and p_i the turbulence parameters. For a flat plate surrounded by turbulent flow the boundary condition at δ will be:

$$V_n = V_i \text{ (turbulent)}$$

For a more general case one can write:

$$V_n \Big|_{\delta} = (V_n^{\ 1} + v_i)\Big|_{\delta}$$

One can approximate v_i by using an equivalent plate concept. The computation of $V_n^{\ 1}$ on the other hand will require knowledge of the viscoelastic properties of a turbulent boundary layer. No such information on viscoelastic properties appears to be available in ship-hydrodynamics literature.

In a laminar boundary layer this viscoelastic effect will by definition be absent and only the previously defined first three terms will be present. In addition the boundary layer thickness will also be a different function for the two possible regimes.

TABLE 1

MODEL CHARACTERISTICS

Length	60.0"
Beam	8.0"
Draft	3.2"
CB	.60
Displacement	33.28 lb
Wetted Surface	4.263 ft^2
L.C.B.	.9" aft

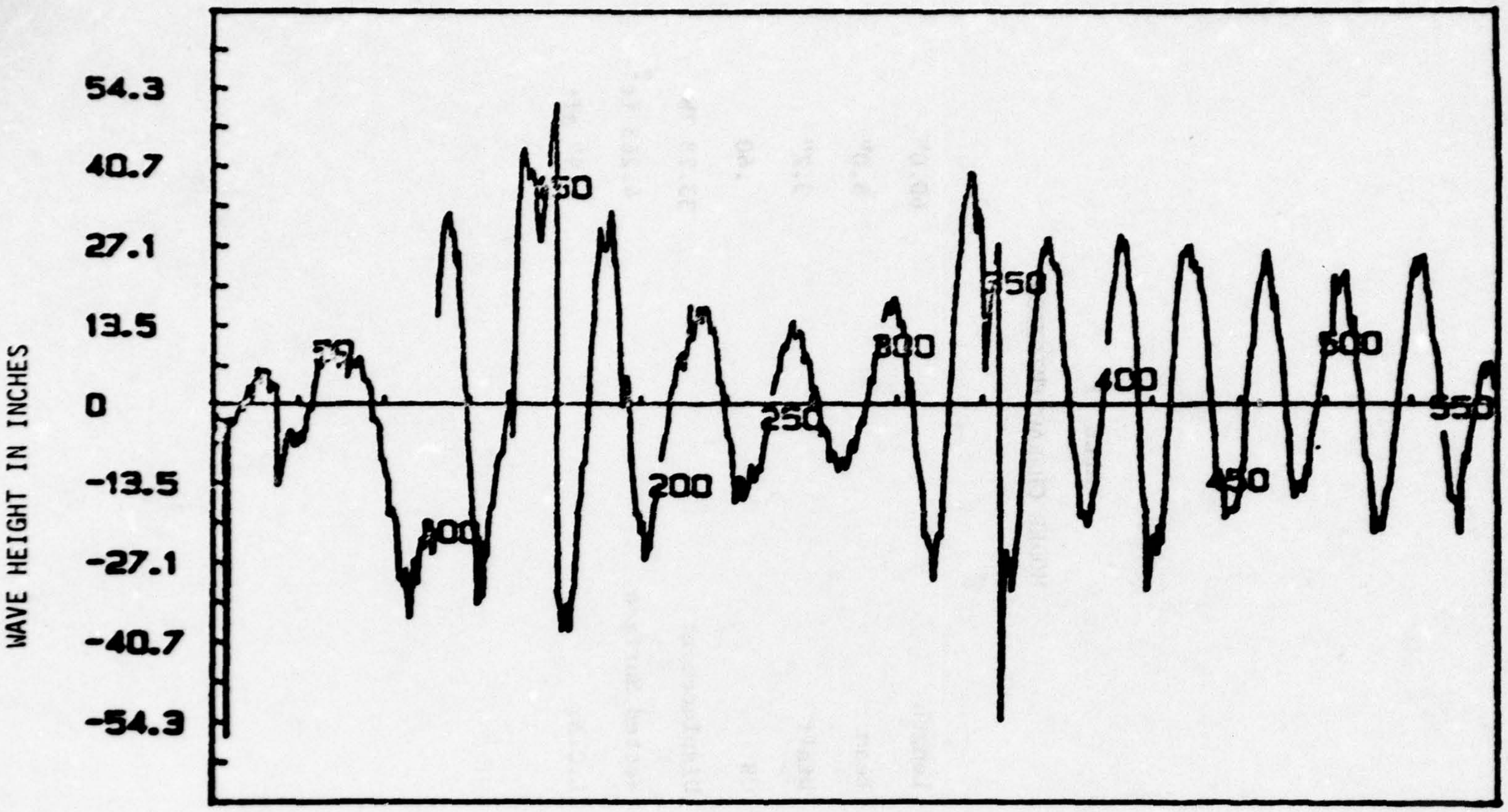

Figure 1

A typical wave height record

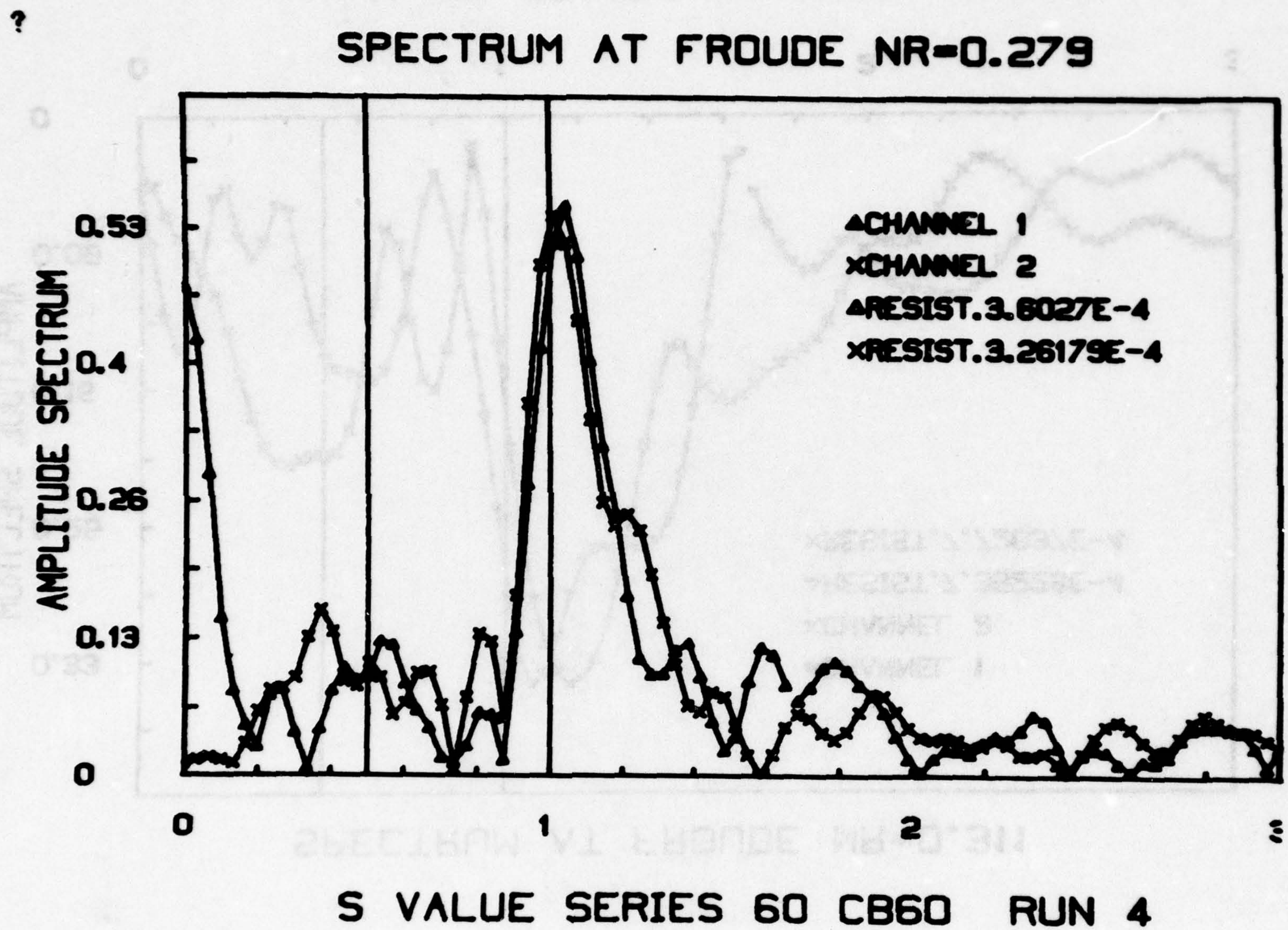

Figure 2 Model & Rough Plate

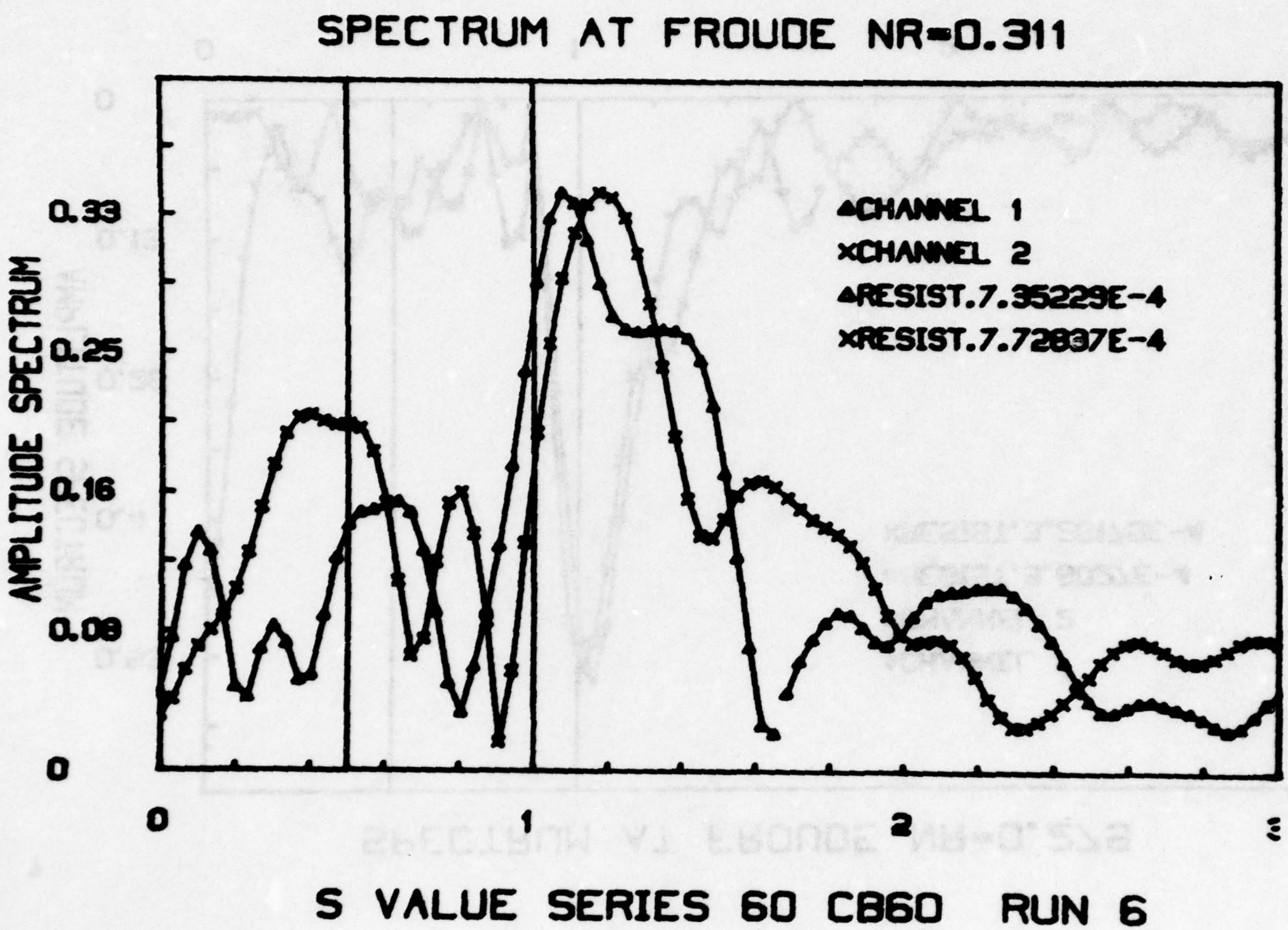

Figure 3 Model & Rough Plate

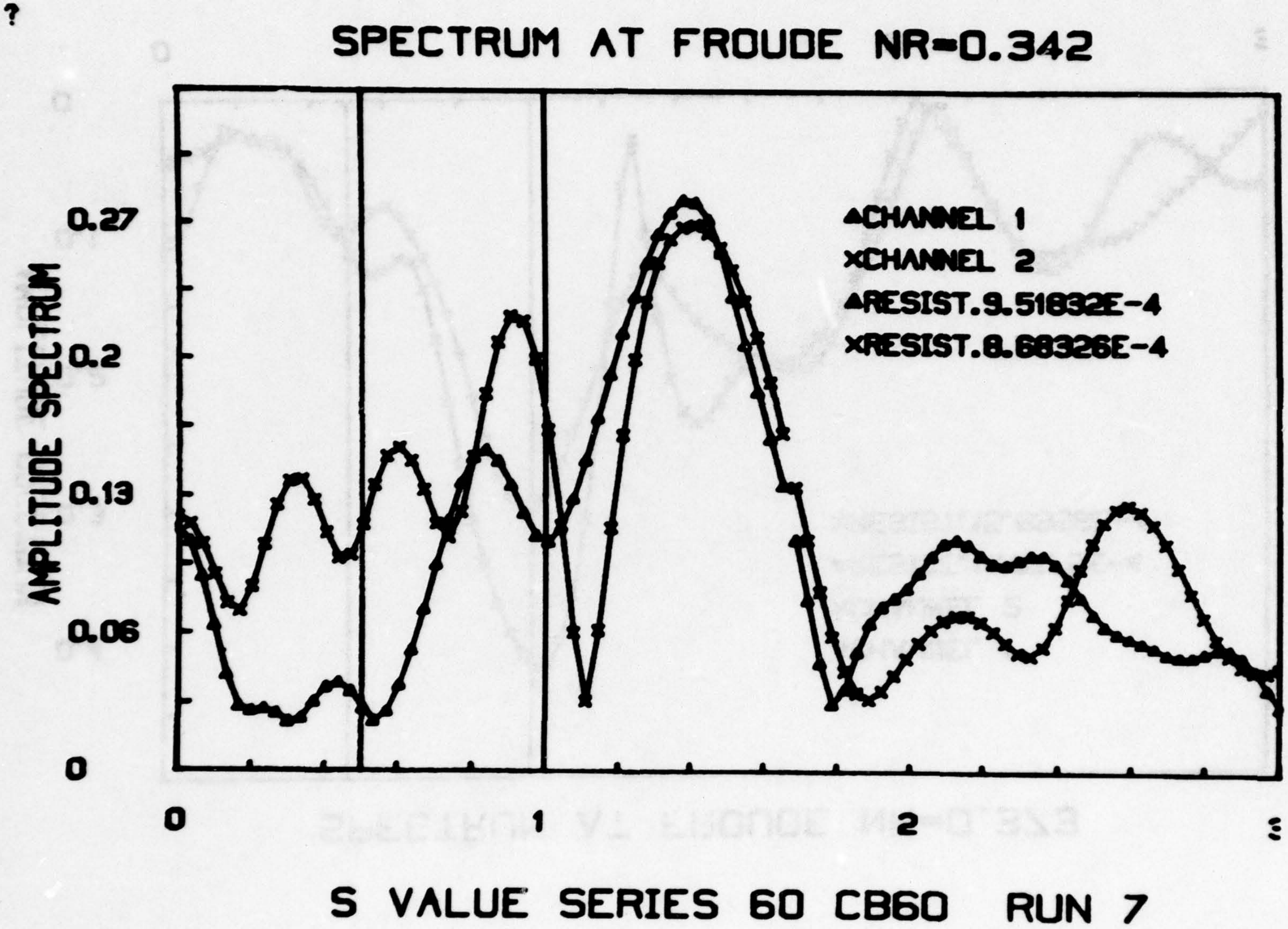

Figure 4 Model & Rough Plate

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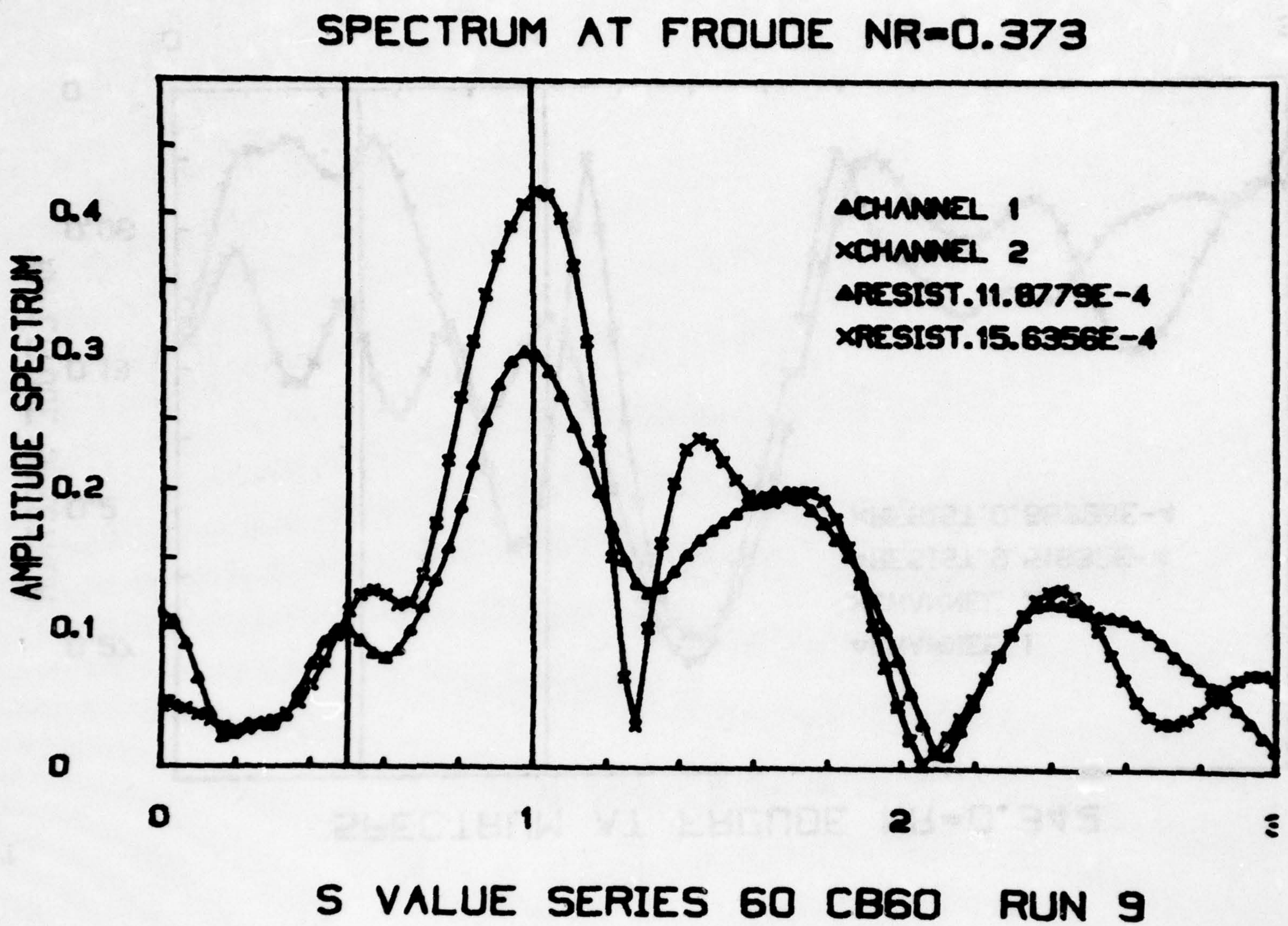
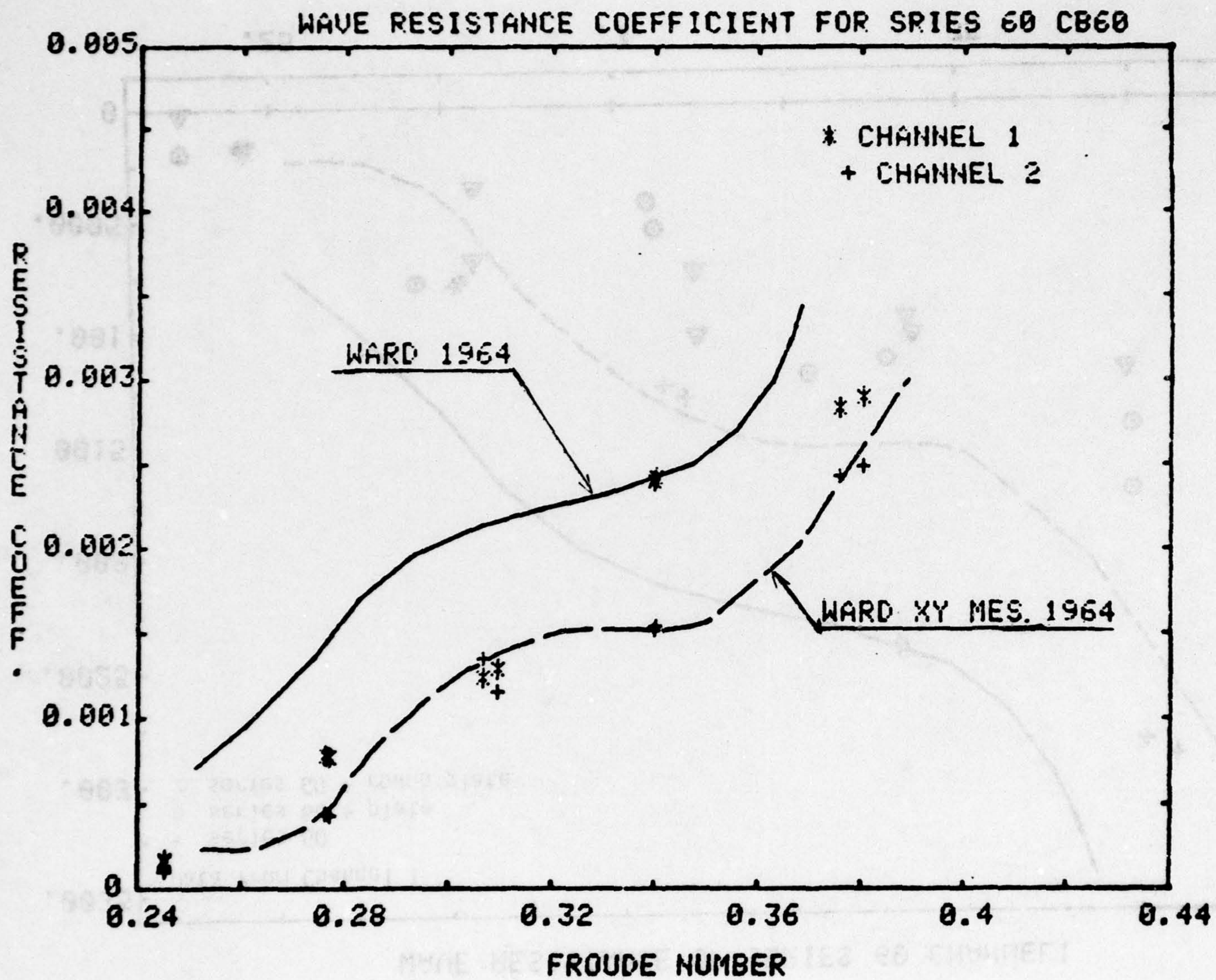


Figure 5 Model & Rough Plate


WAVE RESISTANCE COEFFICIENT FOR SRIES 60 CB60
RESISTANCE COEFF.
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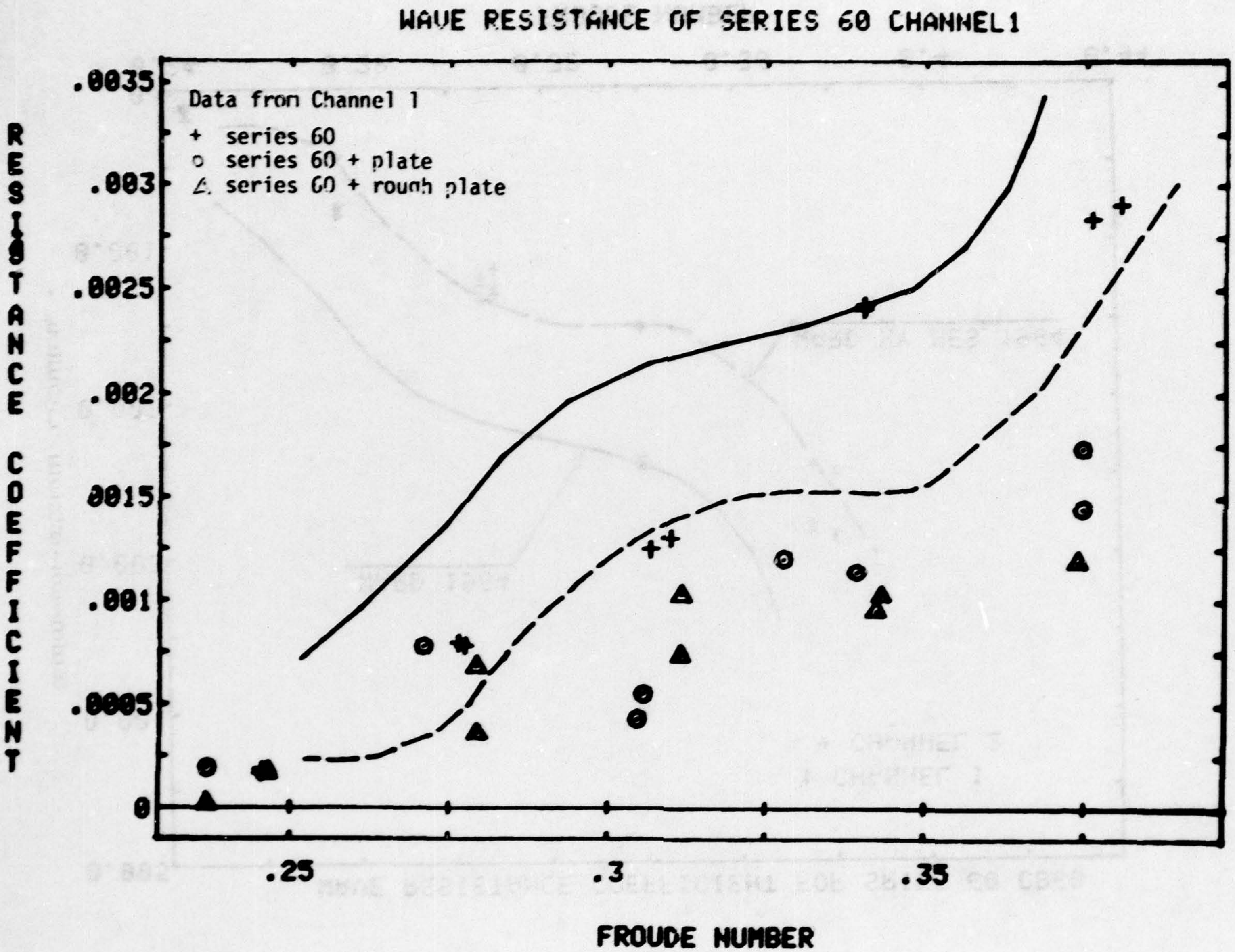
0.004
0.003
0.002
0.001
0
0.24
0.28
0.32
0.36
0.4
0.44
FROUDE NUMBER
* CHANNEL 1
+ CHANNEL 2
WARD 1964
WARD XY MES. 1964

Figure 6


WAVE RESISTANCE OF SERIES 60 CHANNEL1
Data from Channel 1
+ series 60
o series 60 + plate
Δ series 60 + rough plate
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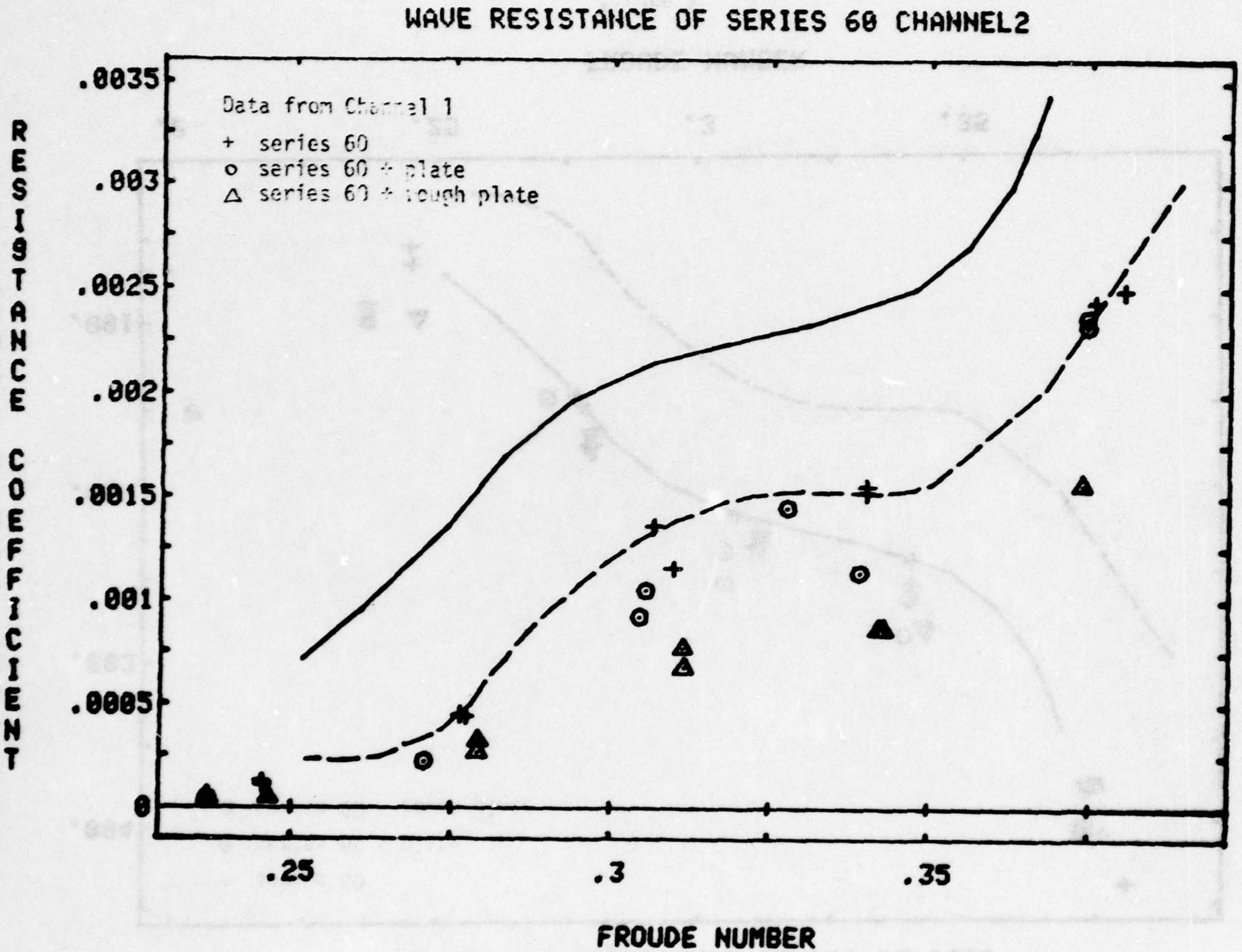
.0015
.001
.0005
0
.25
.3
.35
RESISTANCE COEFFICIENT
FROUDE NUMBER

Figure 7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Data from Channel 1
+ series 60
o series 60 + plate
Δ series 60 + rough plate
RESISTANCE COEFFICIENT
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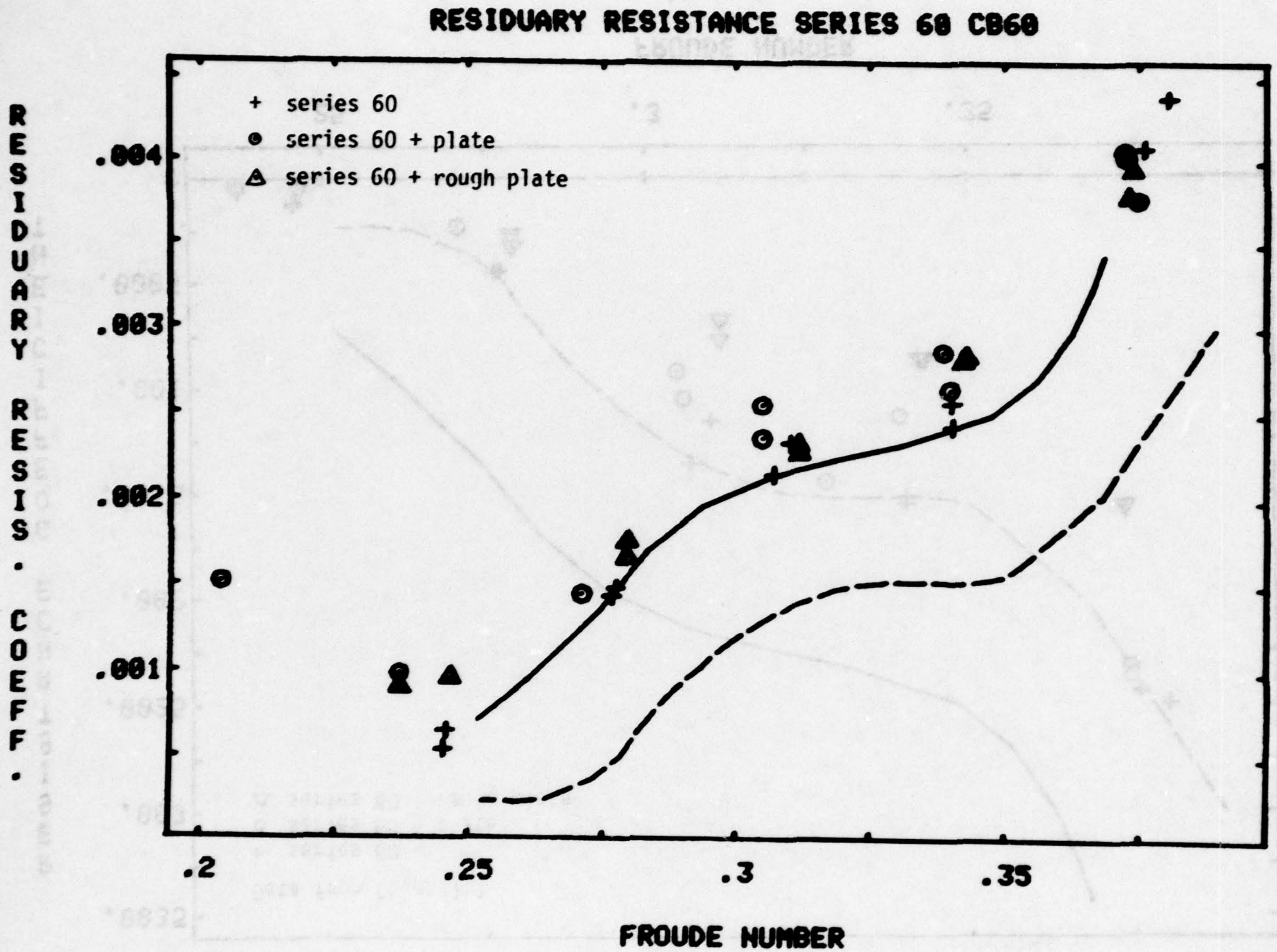
FROUDE NUMBER

Figure 8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+ series 60
series 60 + plate
series 60 + rough plate
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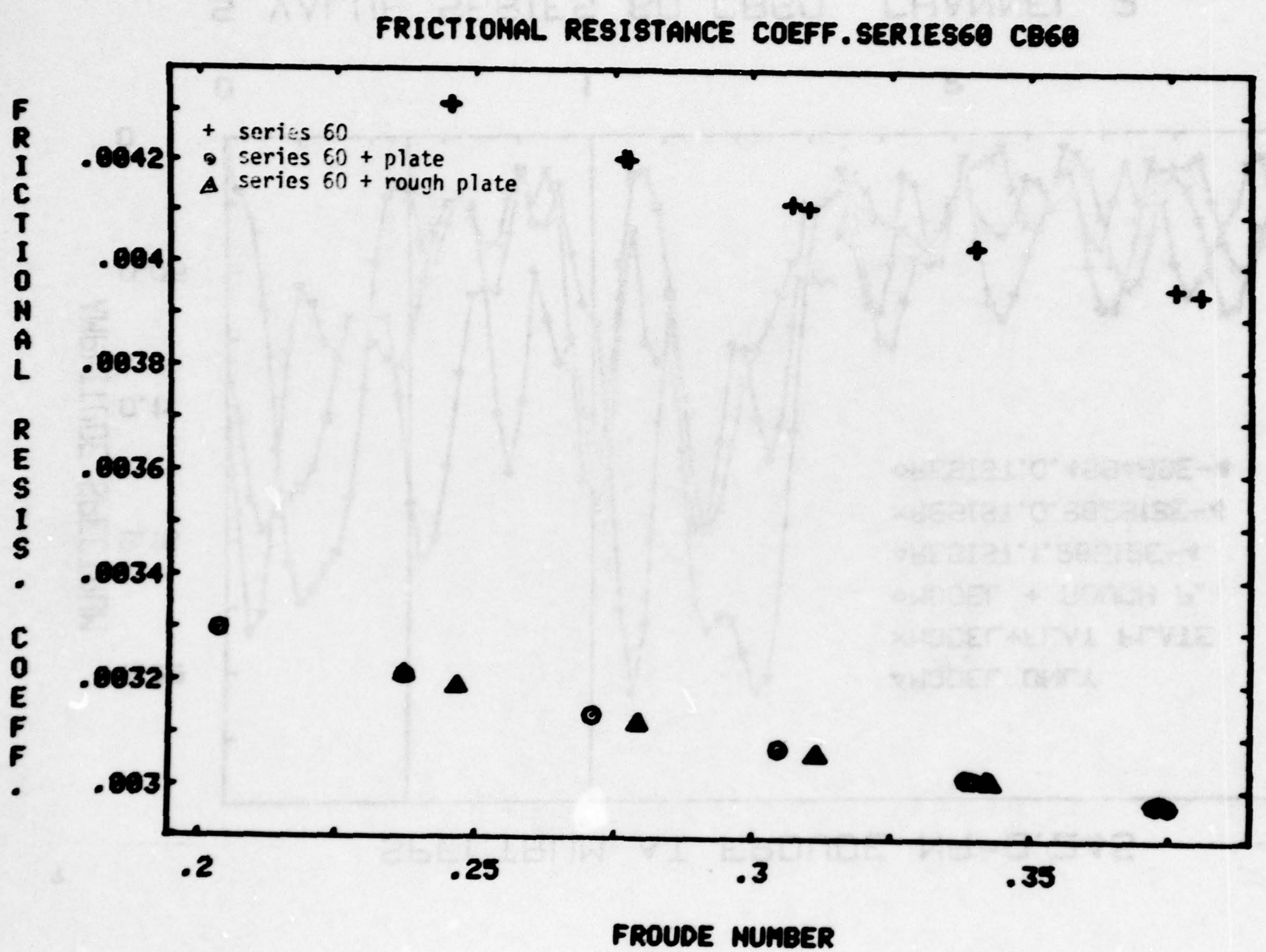
FROUDE NUMBER

Figure 9



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series 60 + plate
series 60 + rough plate
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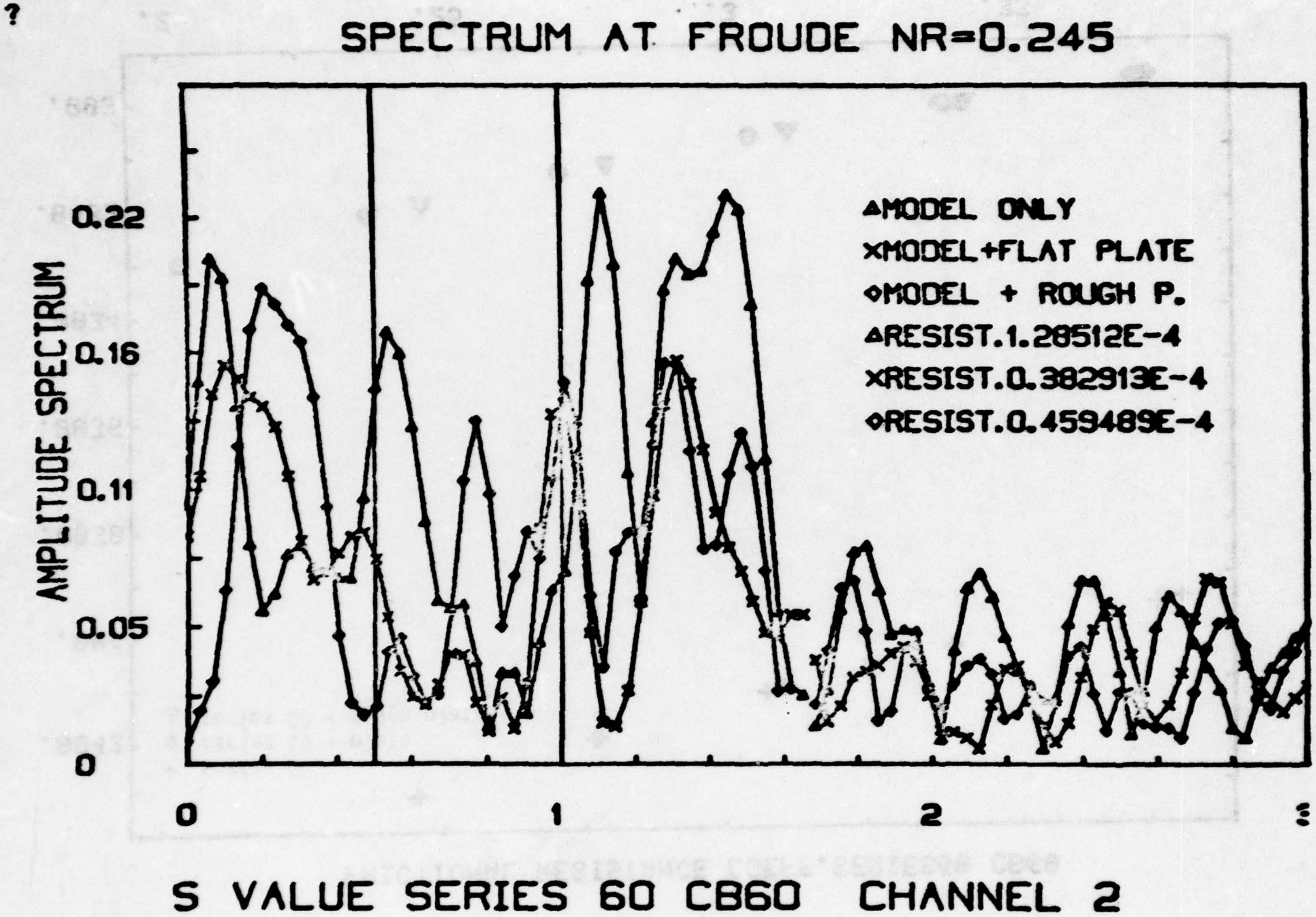
FROUDE NUMBER

Figure 10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0.11
0.05
0
0
1
2
3
ΔMODEL ONLY
×MODEL+FLAT PLATE
◇MODEL + ROUGH P.
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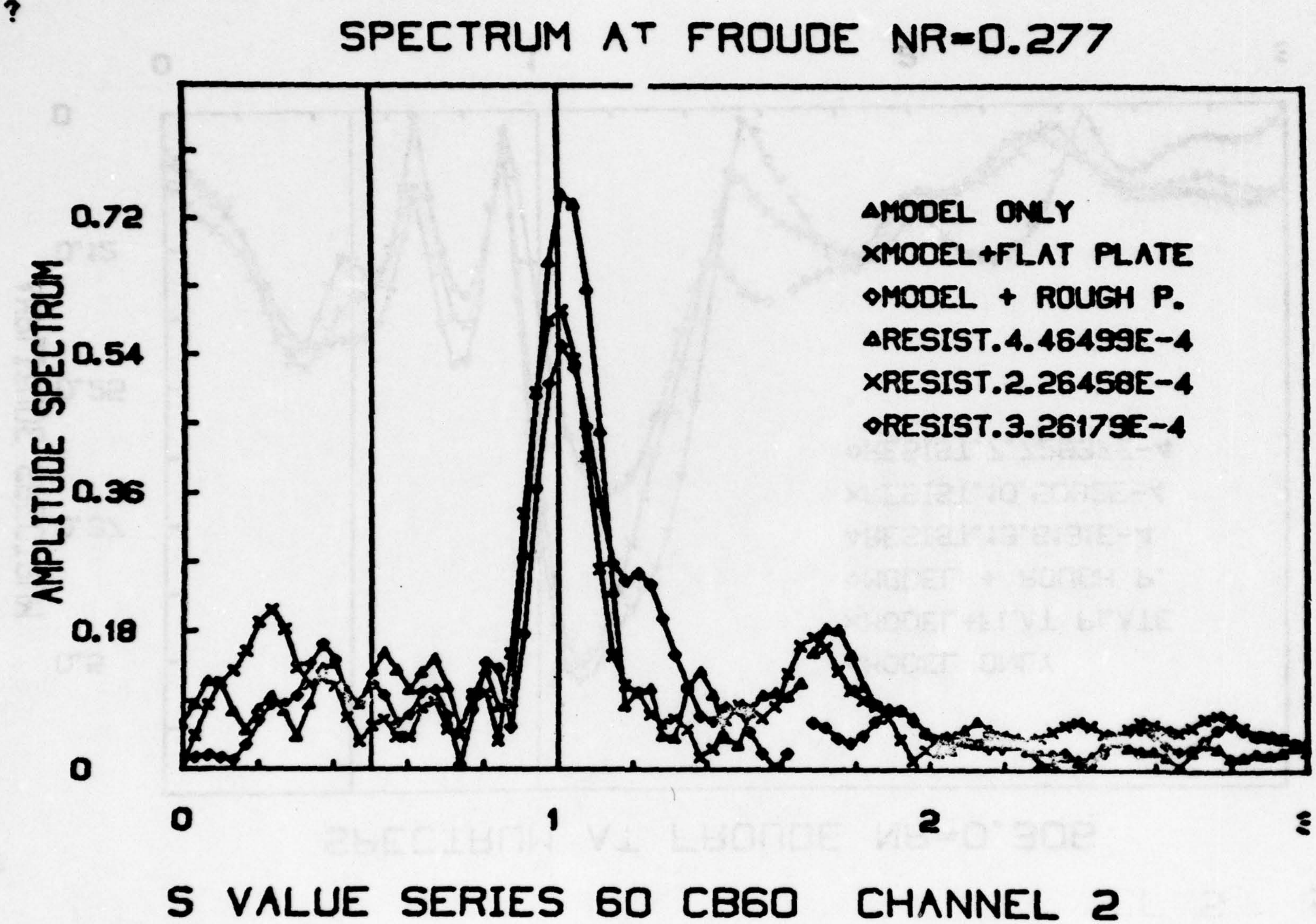
×RESIST.0.382913E-4
◇RESIST.0.459489E-4
S VALUE SERIES 60 CB60 CHANNEL 2

Figure 11



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0.36
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0
0
1
2
3
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×MODEL+FLAT PLATE
◇MODEL + ROUGH P.
ΔRESIST.4.46499E-4
×RESIST.2.26458E-4
◇RESIST.3.26179E-4
S VALUE SERIES 60 CB60 CHANNEL 2

Figure 12

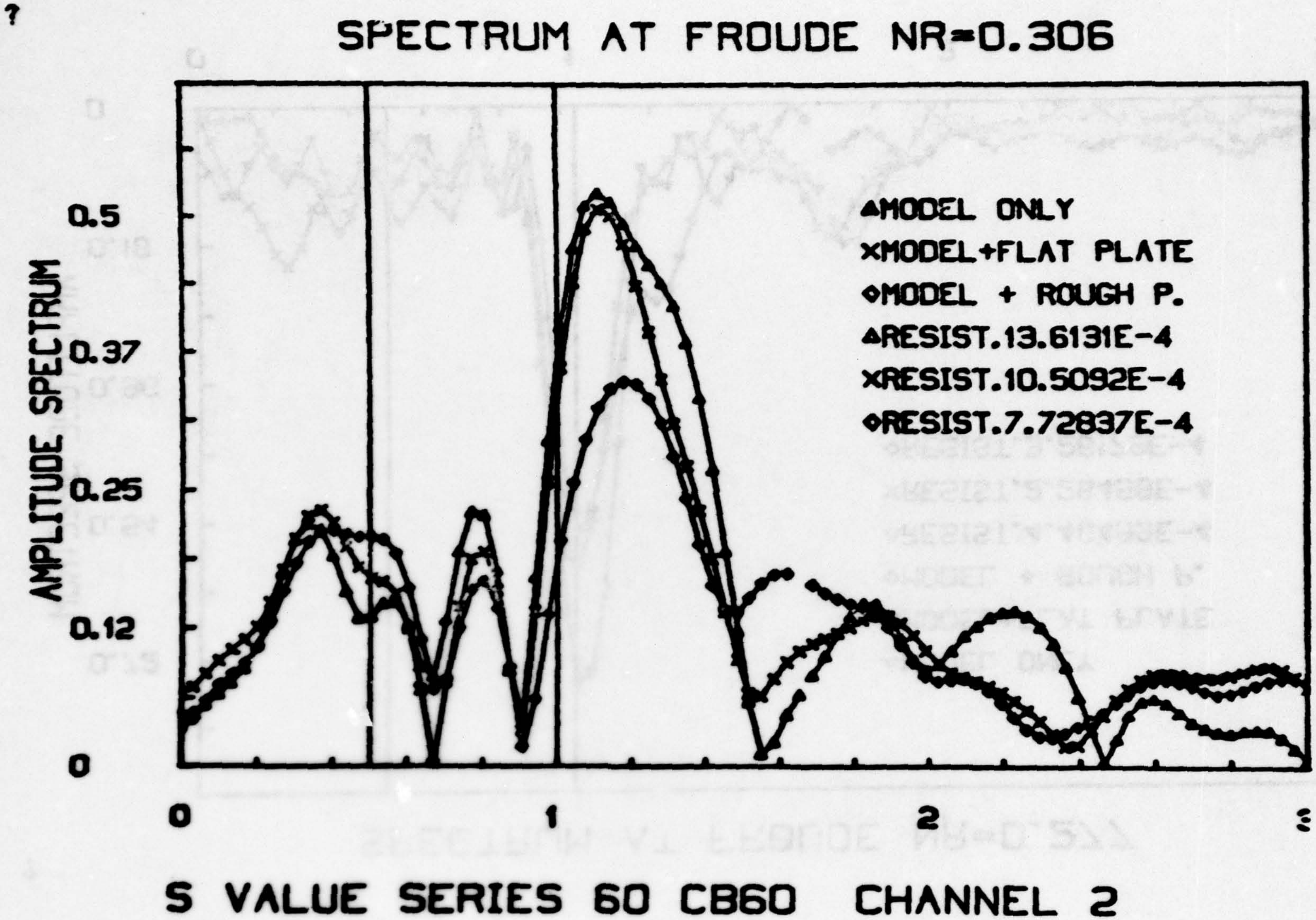
SPECTRUM AT FROUDE NR=0.306
AMPLITUDE SPECTRUM
0.5
0.37
0.25
0.12
0
▲MODEL ONLY
×MODEL+FLAT PLATE
◆MODEL + ROUGH P.
▲RESIST.13.6131E-4
×RESIST.10.5092E-4
◆RESIST.7.72837E-4
0
1
2
3
S VALUE SERIES 60 CB60 CHANNEL 2

Figure 13

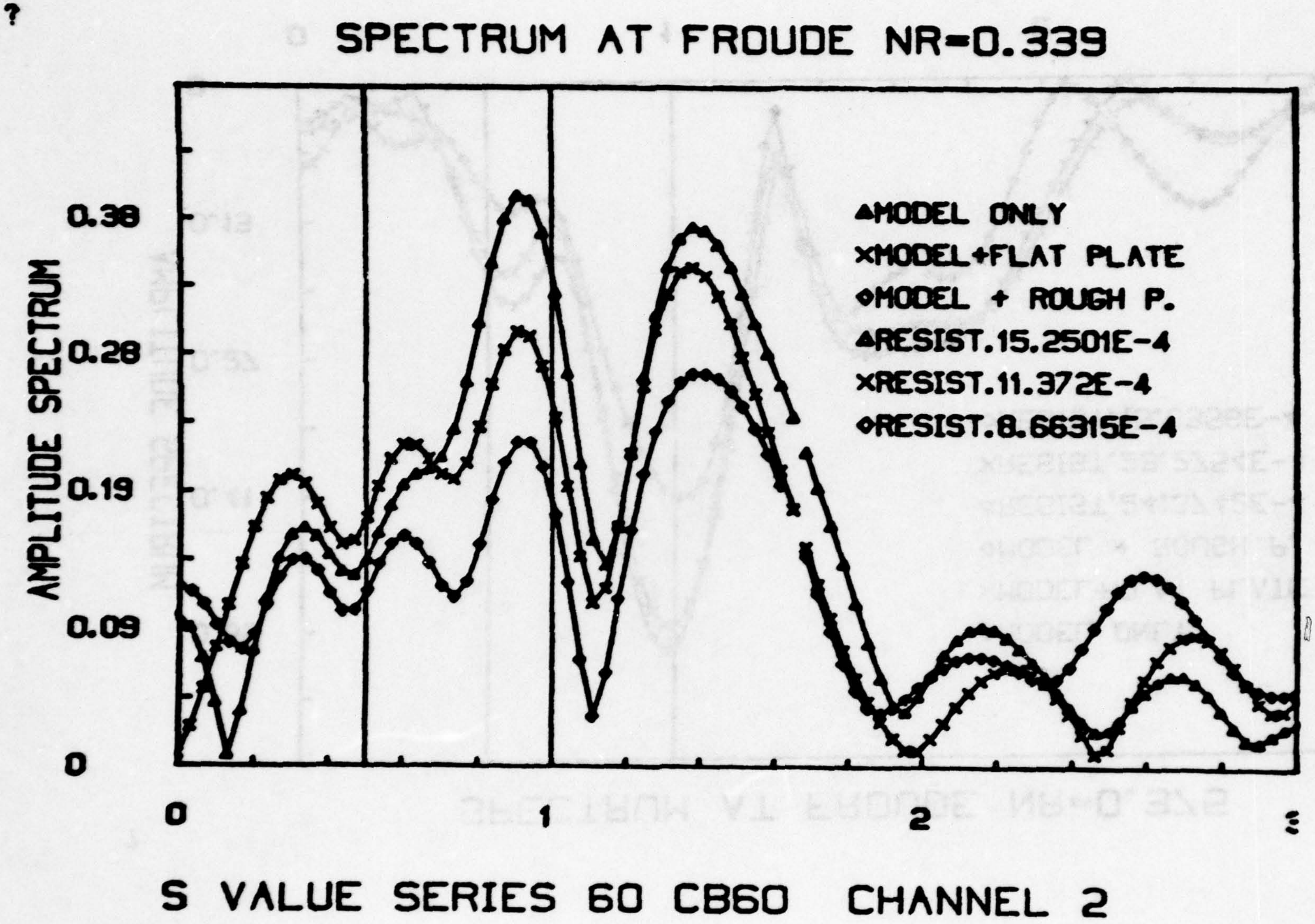
SPECTRUM AT FROUDE NR=0.339
AMPLITUDE SPECTRUM
0.38
0.28
0.19
0.09
0
0
1
2
3
▲MODEL ONLY
×MODEL+FLAT PLATE
◆MODEL + ROUGH P.
▲RESIST.15.2501E-4
×RESIST.11.372E-4
◆RESIST.8.66315E-4
S VALUE SERIES 60 CB60 CHANNEL 2

Figure 14

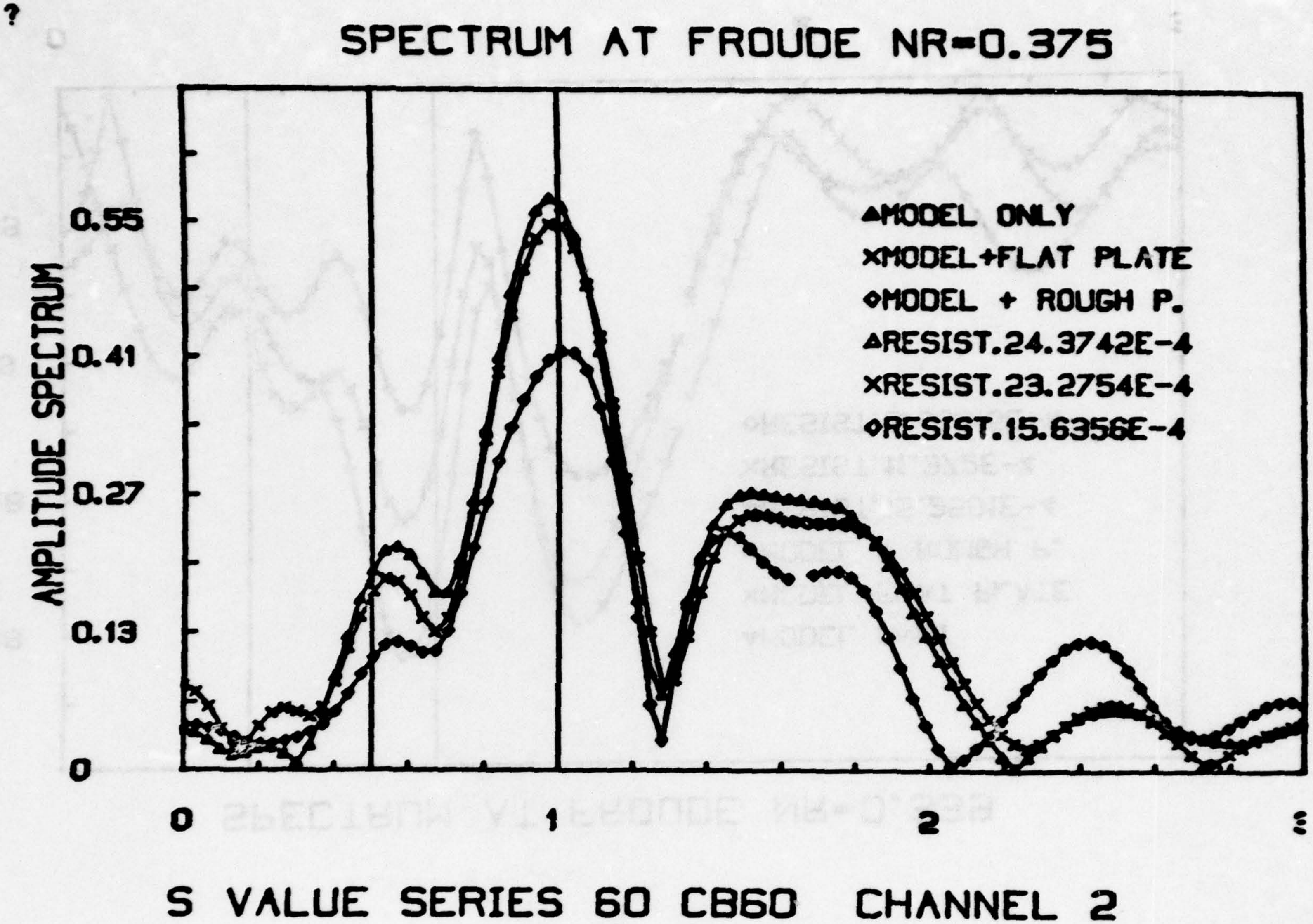
SPECTRUM AT FROUDE NR=0.375
AMPLITUDE SPECTRUM
0.55
0.41
0.27
0.13
0
▲MODEL ONLY
×MODEL+FLAT PLATE
◆MODEL + ROUGH P.
▲RESIST.24.3742E-4
×RESIST.23.2754E-4
◆RESIST.15.6356E-4
0
1
2
3
S VALUE SERIES 60 CB60 CHANNEL 2

Figure 15

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